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**Abstract**. We review two approaches to x-ray lasing using ultra-short pulse (USP) driving lasers in which ionization of the lasant is not via electron collisions. In one approach, the large electric field of the laser beam ionizes a column of plasma along the laser axis. Both linear polarization, with subsequent recombination lasing, and circular polarization, with collisional excitation lasing, can be used. For either type of polarization, ionization induced refraction can limit the lasing length. We review recent experiments and theoretical calculations on ionization induced refraction and on the electron distribution following field ionization. Lasing has been observed with both types of pumping with the collisional variation having the largest gain-length product and the recombination variation having the shortest wavelength. We discuss various ideas to improve the gain coefficient of field ionized x-ray lasers. Another two-step approach to x-ray lasing with USP lasers involves the x-ray photoionization of inner-shell electrons. The first step is to produce a pulse of incoherent x rays with a very rapid rise time by heating a high-Z material with an USP laser. In the second step, a low energy filter removes x rays that can only ionize outer-shell electrons and the remaining x rays primarily ionize inner-shell electrons. This approach has not been demonstrated at x-ray wavelengths but modeling shows that lasing at 45 Å is possible with existing USP lasers and that lasing down to 15 Å should be possible with planned USP laser drivers.

## 1. Introduction

There is an increasing interest in using USP laser to pump x-ray lasers with three major approaches being considered. The first approach uses field ionization, the second uses inner-shell photoionization, and the third uses collisional ionization. In the last approach, peak gain occurs early in the ionization process when the abundance of the lasing ions, e.g., Ne- or Ni-like ions. As the plasma passes through this ionization stage, the electron temperature and the gain coefficient are much higher than that of steady state. There are target design issues associated with refraction and having a narrow gain region that need to be resolved for this approach. In this paper, we will restrict our attention to the first two approaches using USP laser drivers. Through the use of chirped-pulse amplification, high intensity USP lasers can be built which operate at high repetition rates [1,2]. This is an advantage of using USP lasers as drivers for x-ray lasers because the high repetition rates (10 Hz to 1 kHz) lead to high average powers for the x-ray lasers.

The first approach utilizes the high intensity of USP lasers with corresponding large electric fields that can remove electrons from an atom very rapidly. The energy of the ionized electrons depends on their binding energy and the wavelength and pulse shape of the ionizing laser. However, the largest effect on the ionized electron distribution is the polarization of the laser. It was predicted that the use of linear polarization would lead to cold electrons that would rapidly recombine [3,4]. In the first demonstration of recombination lasing following field ionization in H-like Li at 135 Å [5], there remains a question of which ionization method is responsible for the removal of the outer electron. It has been proposed that in the formation of the vapor, the Li plasma does not fully recombine and thus the USP laser pulse is incident on singly ionized Li with cold surrounding electrons [6]. Lasing has been observed at 135 Å in H-like Li at two other laboratories, but in all cases the gain-length product has been relatively small [7,8]. There has also been observation of lasing in C- and N-like O at 374 and 617 Å, respectively, with also a small gain-length [9]. In some of these experiments, it appears that ionization induced refraction is limiting the lasing length and thus the gain-length product that can be obtained. A high-gain length product ($gL$ = 11) has been observed following field ionization at 418 Å in Xe [10]. In this case, circularly polarized light was used. This experiment has not been repeated at another laboratory nor at another wavelength. At the density for which this collisional Xe laser operates, ionization induced refraction is not a serious problem. However, when this scheme is extended to shorter wavelengths which require higher densities, refraction will become a problem. We will discuss the field ionized approach in more detail in the following section.

In all demonstrated x-ray lasers, the lasing transition is between two energy levels associated with an outer electron of a relatively highly ionized ion. In contrast, the inner-shell approach obtains x-ray wavelengths in a singly ionized ion. A large energy efficiency advantage is obtained by not having to remove a large number of outer electrons. However, this advantage is lost because the majority of inner-shell ionizations result in an Auger non-radiative transition. This approach was proposed many years ago [11], but only with the advent of USP lasers does it appear that the problem of collisional ionization of outer-shell electrons may be solved. Recent modeling efforts started with a study of lasing in Ne at 15 Å [12-14]. This wavelength is of particular interest because it is significantly shorter than what has been obtained using other approaches. However, the predicted energy requirements for Ne of at least 10 J is significantly more than has been obtained at the required short pulse duration of order 20 fs. The desire to use existing laser capabilities has motivated modeling in C with lasing at 45 Å [15-17]. To obtain sufficient gain-length product to give clear evidence of lasing in C requires an USP laser with an energy of order 1 J in a 45 fs pulse [18]. With such a short pulse, a traveling wave with a very uniform wavefront must be used. The duration of inner-shell lasing is usually calculated to be less than 100 fs which is an advantage for many applications.

In the next section we review optical-field ionization x-ray laser schemes and in the following section inner-shell ionization x-ray laser schemes. In the last section, we summarize the use of these approaches using USP lasers and give some prospects for future developments.

## 2. Optical-field ionization x-ray laser schemes

Since the last conference in this series [19], the largest breakthrough in optical-field ionized schemes was the demonstration of a large gain-length product in Xe at Stanford University using a circularly polarized USP laser [10]. Using an energy per pulse of only 70 mJ, lasing was observed in Pd-like Xe at 418 Å with a gain-length product of 11 and a repetition rate of 10 Hz. Prior modeling, by the same group, for Ar, Kr, and Xe predicted highest gain coefficients for Xe [20]. The measured gain coefficient is significantly less than predicted with a possible reason being the loss of hot electrons out of the plasma channel, which was not included in the modeling. In contrast to standard collisional excitation schemes, it may prove difficult to reach short wavelengths with this field ionization approach. As the energies of the ionized electrons are increased, by using higher intensity laser pulses, they stay in the ionized channel for a shorter time making collisional excitation more difficult. In addition, to reach short wavelengths one needs not only higher energy electrons but also higher ion and electron densities. At these higher densities, ionization induced refraction becomes a problem as well. Despite these potential problems in scaling the collisional field-ionized approach to short wavelengths, this demonstration of table-top lasing is very exciting.

The first demonstration of lasing using field ionization was H-like Li at 135 Å at RIKIN in Japan with the upper-laser state being populated by recombination [5]. Similar observations of lasing in H-like Li were made at other laboratories [7,8]. These early observations motivated significant theoretical and experimental research on field-ionized schemes, in particular, schemes based on recombination. The two areas of primary interest are ionization induced refraction and electron temperature following ionization. In addition to these H-like Li experiments, there was also observation of lasing in C- and N-like O at 374 and 617 Å respectively [9]. As was the case in Li, there was observation of a large gain coefficient ($g$ > 10/cm), but only a small gain-length product of order 1. (For H-like Li, the gain-length products were of order 4.) For one of the H-like Li experiments [7]. there has been modeling of ionization induced refraction that predicts a limiting of lasing length and thus a reason for the modest gain-length product [21]. Following a short discussion of refraction, we discuss the issue of the electron distribution following ionization, and ideas to increase the gain for field-ionized schemes.

For field ionized x-ray laser experiments in O and Li, the USP laser is focused onto a gas jet or a similar structure, e.g., a laser evaporated gas. The experiment in Xe used a gas cell with pinholes to define the lasing length. In all cases, the laser has maximum intensity on axis and thus one has maximum electron density on axis following ionization. For the case of static field where the laser passes through the gas during focusing, there are theoretical arguments that predict a limiting intensity and thus electron density that can be obtain because of refraction [21]. For gases with a rapid decrease in density at the edge, such as gas jets, one can have focusing in vacuum and high laser intensities incident on the gas. This can give much higher electron densities than can be obtained using a static fill. For x-ray laser applications, it is critical to have high electron density over a significant length to obtain a larger gain-length product. A model that self-consistently evolves the laser radiation as it ionizes the gas predicts that the lasing length for the H-like experiments done at Berkeley is 1.2 mm [21]. In the experiment, faster than linear growth was observed only for lengths less than 1.5 mm, which is consistent with the modeling [7]. The same modeling code was used to calculate transmitted energy through Al vapor with good agreement with observations

[22]. In another study of ionization-induced refraction, small scale breakup of the laser was observed in addition to whole beam defocusing [23]. One way to reduce the effects of refraction is to use very large focal spots. However, this requires significantly more laser energy. The needed energy can be reduced by considering ions that require less intensity, e.g., Li-like N [21,24]. Initial experiments have been tried in Li-like N with no evidence of lasing [25]. Another way to avoid ionization induced refraction is to form a plasma channel. Plasma channeling has been observed with the laser intensity remaining high over long lengths [26]. It has not been demonstrated that the conditions necessary for lasing are achieved inside of the plasma channel.

There have been a significant number of theoretical and experimental efforts to understand the electron distribution following ionization. For the case of a Li plasma, there is a conjecture that gain is enhanced because of a two temperature plasma. One idea for the origin of a cold component is that the Li is singly ionized when the USP laser pulse field ionizes the remaining two electrons [6]. The electrons that are already ionized could have significantly less energy than what they would have if they had been field ionized. However, modeling places limits on the effectiveness of the cold component [27]. For the experiments in O and the proposed ones in N, the electrons are expected to be all field ionized. Calculations show that the energy of the ionized electrons, using a linearly polarized laser, can depend on the rise time of the ionizing pulse [28]. A slow rise in the pulse minimizes ATI heating and a rapid fall minimizes inverse brehmsstrahlung. Modeling is in reasonable agreement with experiments [29,30]. Experiments have clearly shown that the electron distributions can be non-Maxwellian [29]. Existing atomic kinetic modeling codes will have to be adapted to include such electron distributions in the calculation of gain coefficients for field ionized x-ray lasers. Extending the recombination variation to short wavelengths has been shown to be difficult because of stimulated Raman scattering at the required high intensities [30,31].

There have been a number of ideas proposed to increase the gain coefficient of field ionized x-ray lasers. Because most recombination schemes lase down to the ground state, to achieve short wavelengths, the lasing self-terminates as the ground state is filled because there is negligible emptying of the state. There has been modeling to show the benefit of the removal of ground-state electrons during lasing via a broadband ionizing radiation field [32]. A rather complicated scheme has been proposed where an electron is excited to a high Rydberg state prior to ionization by the USP laser [33]. If this electron is not ionized, as they suggest because of stabilization, and can be induced to a lower state by a secondary laser, one can create a large population inversion between this state and the ground state. One can also try to lase between states where the degeneracy of the lower-laser state is significantly larger than the upper-laser state [9,34]. It would be a major advance for the recombination variation to achieve a gain-length product of order 10 and it is possible that some of these ideas will aid in that goal.

## 3. Inner-shell ionization x-ray laser schemes

X-ray lasing is possible following very rapid inner-shell ionization. The majority of the photoelectrons and all of the Auger electrons have sufficient energy to ionize outer electrons. For the schemes considered here, the ionization of an outer electron from a neutral atom directly populates the lower-laser level. The time required to significantly populate the lower-laser level depends on the ion density and the electron energy distribution. If the density is decreased too much, as a way to slow down the collision time, the gain coefficients become too small. For densities approximately one thousandths of solid density, reasonable gain coefficients are calculated provided the ionization is sufficiently rapid ($t$ < 50 fs). The need for an USP driving lasers enters in the requirement to have an incoherent pulse of x rays with enough energy to ionize inner-shell electrons and with a rapid rise time. When a high-Z material is heated rapidly by an USP laser, it can produce such a pulse of x rays. High intensity is also required because the pulse must be intense enough to compete with the very rapid non-radiative Auger decay of the upper-laser level. The incoherent x rays need to pass through a filter to remove photons with less energy than that required to ionize inner-shell electrons. These low energy photons, if not filtered out, would ionize outer-shell electrons and provide an additional mechanism for populating the lower-laser state.

Modeling efforts have concentrated on lasing in Ne at 15 Å and in C at 45 Å [11-18]. With a sufficient source of ionizing x rays, this scheme based on K-shell ionization can be extended down to approximately 5 Å. For present and planned USP lasers, the wavelength range between 15 and 45 Å is of primary interest. Details of target design and gain calculation for C are presented in another paper in these proceedings and we will only summarize the results [18]. The modeling shows that the creation a sufficient gain-length product to give clear evidence of lasing in C requires an USP laser with an energy of order 1 J in a 45 fs pulse. A modest increase in the gain coefficient by 50% is calculated if the same energy is delivered in a 15 fs pulse. Little benefit is found for pulses shorter than 15 fs which is approximately the time required for a high Z material, e.g., Au, to become sufficiently ionized to produce the desired x rays. The duration of lasing using a 45 fs driving pulse is 60 fs. For many applications of coherent and incoherent x rays having a duration less than 100 fs is important to resolve the dynamics of interest. Energy requirements for Ne are a least an order of magnitude higher. The good news is that USP petawatt lasers (20 J in 20 fs) are planned and should become available in a few years [35,36]. In contrast to field ionized schemes, inner-shell schemes require side pumping using a line focus as is the case for conventional x-ray lasers. The short duration of lasing means that a traveling wave excitation is required and given that in 20 fs light only travels 6 microns, it will be necessary to have a very uniform wavefront.

## 4. Summary and future prospects

For field ionized schemes, the biggest advance in the last two years was the demonstration of a large gain-length product in Xe at 418 Å using a circularly polarized USP laser with only 70 mJ per pulse and a 10 Hz repetition rate. The observation of recombination lasing in O at 374 and 617 Å was also very interesting. However, achieving a large gain-length product at reasonable short wavelengths ($\lambda$ < 200 Å) has not yet been demonstrated. It should also be noted that for wavelengths longer than 100 Å, the use of USP lasers to produce high harmonic emission is a very competitive source of coherent x rays. The difficulty of achieving significant emission via harmonics for short wavelengths ($\lambda$ < 50 Å) is one reason that inner-shell schemes are being considered more seriously. One reason that inner-shell schemes have not been tested extensively is the relatively complex design consisting of a high Z material to produce x rays, a low Z material to filter low energy photons, and a low density lasant. However, the prospects for inner-shell lasing in the near future appear to be good given the major advances expected in the USP driving lasers. In particular lasing around 45 Å should be possible very soon. The number of laboratories having USP lasers with powers in excess of a terawatt is rapidly increasing. Thus, the future prospects for lasing based on optical-field and inner-shell ionization appears to be very good.

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